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(54) **Steam injected engine with auxiliary high pressure steam turbine.**

(57) A steam injected gas turbine engine, including a compressor, a combustor, a high pressure turbine and a power turbine for producing the output power for the engine. A high pressure boiler is included downstream of the power turbine to produce superheated steam at very high pressures and high temperatures. The steam passes through an auxiliary steam turbine for extracting power output from the steam to increase the engine output. The steam is injected back into the engine, as for example, directly into the combustor. The thermal efficiency and power output of the engine system is substantially increased thereby at constant high pressure turbine rotor inlet temperature.

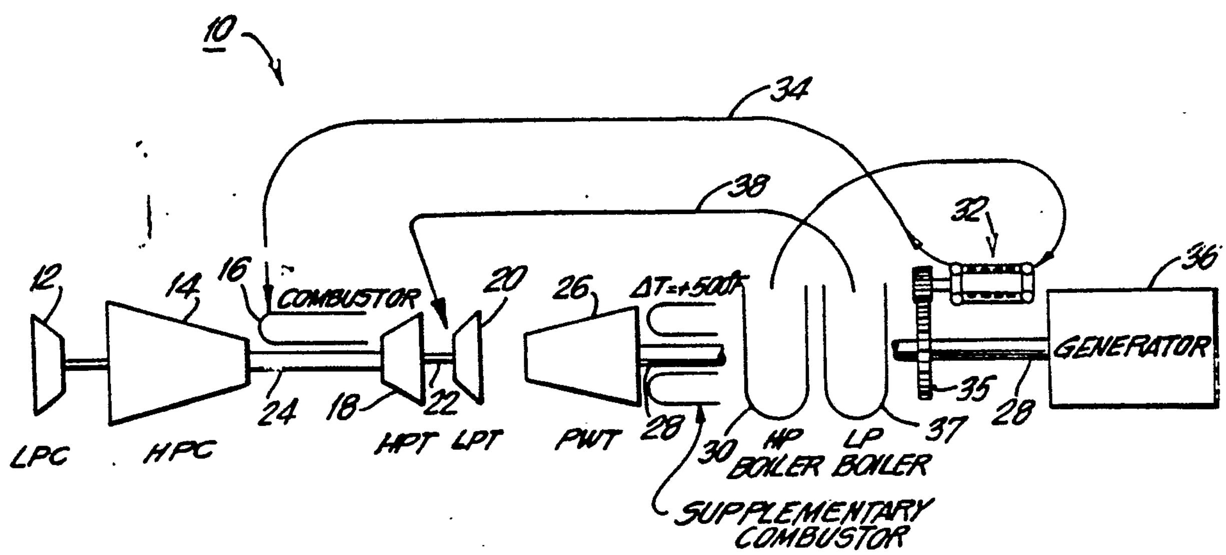

FIG. 1

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STEAM INJECTED ENGINE WITH AUXILLARY HIGH PRESSURE STEAM TURBINE

This invention relates to gas turbine engines, and more particularly, to a steam injected gas turbine engine having a small auxillary high pressure steam turbine for extracting additional horsepower output from the engine and improving cycle thermal efficiency.

BACKGROUND OF THE INVENTION

The use of steam injection for improving the performance of a gas turbine engine is well known. Such engines typically generate the steam from waste heat emitted from the engine and inject the steam into the cycle for improving the performance of the gas turbine. One such typical arrangement is described in U.S. Patent 4, 569, 195 to Johnson and assigned to the assignee of the present invention. In this patent steam is generated in an exhaust heat exchanger either from engine exhaust heat alone or in combination with the heat from one or more supplemental combustors or burners placed in the exhaust system. The steam produced is then injected into the engine. Injection can be in any of various portions of the engine, including the main combustor, or various ones of the turbines, including the low pressure turbine, the high pressure turbine, or the power turbine.

Various boilers can be placed downstream of the power turbine where steam at intermediate and low pressure is generated, with the steam then injected into various parts of the engine.

Nevertheless, a great amount of the steam flowing in the engine leaves the open cycle engine as uncondensed vapor, which is a loss, thereby reducing the thermal efficiency of the engine. Accordingly, while the use of steam injection has improved the operation of gas turbine engines, much of the steam leaves the engine whereby the efficiency and the power output is not as large as could be possible.

SUMMARY OF THE INVENTION

The present invention achieves an improvement in both cycle thermal efficiency, as well as system power output of a steam injected gas turbine engine, by utilizing a high pressure boiler downstream of the power turbine to produce steam at very high pressure and temperature. The steam then passes through a high pressure steam turbine which is non-condensing (hereinafter referred to as an auxiliary steam turbine) whereby horsepower is extracted from this superheated steam, resulting in much cooler steam which is still above saturation and still has enough pressure for combustor injection. The cool steam can be either injected directly back into the combustor or can be reheated to a much higher superheat temperature and then injected into the combustor. The cool steam could also be used for cooling static vane parts rather than being reheated. By using a boiler's capability to produce very high pressures efficiently, less uncondensed vapor will be leaving the open cycle at a constant total fuel flow to these engine systems. Table 1 shows that at constant high pressure turbine rotor inlet temperature but with increased fuel flow to the engine system, that the same amount of uncondensed vapor leaves the open cycle. This will significantly improve cycle thermal efficiency. At the same time, the output from the auxiliary steam turbine can be merged into the direct output of the power turbine through an auxiliary turbine gear box whereby the system horsepower output is also improved. Use of an auxiliary steam turbine would not require changes in engine control areas such as high pressure turbine, low pressure turbine, or power turbine nozzle diaphragm areas. However, the regenerator or boiler systems would have to be designed for using an auxiliary steam turbine.

It is accordingly an object of the present invention to provide a gas turbine engine, and a method of engine operation, which increases power output and improves thermal efficiency.

Another object of the present invention is to provide a steam injected gas turbine engine utilizing an auxiliary steam turbine for extracting horsepower from steam produced in a high pressure boiler downstream of the power turbine.

Still a further object of the present invention is to provide a gas turbine engine having a high pressure boiler downstream of the power turbine and producing superheated steam at very high pressures which steam passes through an auxiliary steam turbine and is then injected back into the engine.

Yet a further object of the present invention is to provide a steam injected gas turbine engine having less uncondensed vapor lost in the exhaust from the engine for a given fuel flow rate to the engine system.

Briefly, the present invention in one form provides a gas turbine engine having a compressor, a combustor, and a high pressure turbine in series combination. The output from the engine is extracted through a power turbine. Downstream of the power turbine is a high pressure boiler for providing superheated steam at very high pressures. An auxiliary steam turbine receives the steam from the high pressure boiler and extracts power from the steam in addition to the power output extracted through the power turbine, to thereby increase the engine output power and thermal efficiency. The steam is then injected back into the engine.

In an embodiment of the invention, the steam is reheated in a superheater prior to its injection back into the combustor. In another embodiment of the invention there is further included downstream of the power turbine intermediate pressure boilers and/or low pressure boilers for generating steam for injection into other parts of the engine, such as the turbines.

The steam from the auxiliary steam turbine can also be used to cool static vane parts rather than being reheated in a superheater. Alternately, it can be injected directly into the combustor for cooling the combustor.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagrammatic view of one embodiment of the present invention.

Fig. 2 is a diagrammatic view of another embodiment of the present invention;

Fig. 3 is a T-S (temperature-entropy) diagram of the Rankine cycle showing the increase in efficiency resulting from using the auxiliary steam turbine and high pressure boiler.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is directed towards a land or sea based gas turbine engine using boiler systems in order to provide for heat recovery in the exhaust. The gas turbine typically includes compressors, such as low and high pressure compressors, followed by a combustor after which are turbines, such as the low and high pressure turbine. The output is taken through a power turbine. The present invention further includes a high pressure boiler downsteam of the power turbine designed to produce superheated steam at very high pressures. This steam passes through an auxiliary steam turbine which extracts horsepower from the steam. The steam is still left with enough pressure and at a temperature above saturation, so that it can be injected back into the combustor or other parts of the engine.

With this arrangement, the cycle thermal efficiency of the engine increases, as well as its power output. Such increase results from the reduction of uncondensed vapor lost in the exhaust at a referenced fuel flow rate. Additionally, the boiler has a capability of creating very high pressures with very low pump losses. Furthermore, any pressure losses in the auxiliary steam turbine are not significant, since the boiler can easily make pressure at only a small loss in steam temperature or mass flow. An additional benefit is the fact that a characteristic of superheated steam is that it is not a perfect gas. At constant temperatures, within the temperature range that is being operated on, its enthalpy is increased as the flow is throttled. Accordingly, at the output of the auxiliary steam turbine, where the temperature has been reduced, the pressure has also been significantly decreased while passing through the auxiliary steam turbine and the imperfect gas is now at a higher enthalpy than it would have been if it were a perfect gas at the same temperature, but at a higher pressure.

Referring now to Fig. 1, there is shown generally a gas turbine engine at 10, which includes, in operating fluid sequence, a low pressure compressor means 12, followed by a high pressure compressor means 14. A combustor 16 receives fuel, as is well known in the art, and generates combustor output products, which are sent into a high pressure turbine means 18 followed by a low pressure turbine means 20. A dual shaft system is utilized with the inner shaft 22 from the low pressure turbine driving the low pressure compressor, and the outer shaft 24 from the high pressure turbine driving the high pressure compressor.

The operating fluid then passes from the low pressure turbine for expansion through a power turbine 26, which is then used to drive output devices through the output shaft 28. Typically, steam would be injected into the combustor or other parts of the engine. Some of the steam would be exhausted from the system and leaves the open cycle as uncondensed vapor, which is a loss to the system, thereby reducing the cycle thermal efficiency.

In the present invention, there is added to the engine a high pressure boiler 30 downstream of the power turbine. Typically, the high pressure boiler is designed to produce superheated steam at very high pressures. By way of example, the pressures can be in the range of 1500-3500 psia and superheated steam of at least 750° F.

An auxiliary steam turbine, shown generally at 32 receives the steam output from the high pressure boiler. The steam passes through the auxiliary steam turbine 32 and then along line 34 is injected back into the combustor. The auxiliary turbine can typically operate at about a 4 to 1 pressure ratio. In so doing, it would still leave the steam above saturation and still having enough pressure for combustor injection.

An advantage of this arrangement is that the superheated steam is not a perfect gas, and as a result, at the operating temperatures, its enthalpy is increased as the flow is throttled. At the output of the auxiliary turbines, the temperature of the steam has been reduced from its input. The pressure has also been significantly decreased. As a result, the steam, an imperfect gas, is now at a higher enthalpy than it would have been if it were a perfect gas at the same temperature but at a higher pressure.

The output from the auxiliary turbine 32 could be sent through a gear box 35 or a variable speed constant frequency device, or the like, in order to obtain desired speeds. By way of example, the gear box could use a 6 to 1 ratio to obtain speeds of 3,600 or 3,000 R. P. M. (60 Hz. or 50 Hz.). As is shown, the gear box 35 operates to merge the output from the auxiliary turbine with the main shaft 28 so as to operate the 60 Hz. generator 36.

In addition to the high pressure boiler 30, there can be included other boilers, such as the lower pressure boiler 37 producing steam along line 38, which is then injected into one of the turbines, herein shown as being injected into the low pressure turbine 20.

As shown in Fig. 1, the steam output from the auxiliary steam turbine 32 is injected directly into the combustor. Since the steam is at a rather cool temperature, it would serve to cool the combustor.

Referring to Fig. 2, wherein like parts are identified by like characters, it is shown that the output from the high pressure boiler 30 is sent to the auxiliary steam turbine 32 as before. However, prior to injection of the steam into the combustor, it is first passed through a superheater 40 which is placed between the power turbine 26 and the high pressure boiler 30. As a result, the steam is reheated to a much higher superheat temperature and is then injected into the combustor. The superheater also finds additional use should a supplementary burner be included after the power turbine. Such supplementary burner would increase the temperature at the output of the power turbine, which would raise the temperature substantially at the entrance to the high pressure boiler. Such high temperatures would require special boiler materials. The high pressure superheater 40 would remove such heat before the boilers in order to reduce this temperature.

Instead of using the superheater, the cool steam, as is produced directly from the auxiliary steam turbine could actually be used for cooling various engine parts, such as the static vane parts, rather than being reheated.

As shown in Fig. 2, there is also provided an intermediate pressure boiler 42 and a low pressure boiler 44. The output from these boilers can be used to feed various turbines or other engine parts. As is shown, the steam from intermediate pressure boiler 42 is injected along line 46 to the low pressure turbine 20 and at line 48 into the power turbine 26. Likewise, the power turbine receives steam injection from the lower pressure boiler 44 along line 50. Fig. 2 also shows the use of an intercooler, shown generally at 52.

The output from the auxiliary steam turbine 32 could also be used to drive auxiliary compressors, which could pressurize the intermediate and low pressure boiler steam from the boilers 42 and 44. This steam could then also be injected directly into the combustor. In this way, the auxiliary compressor losses would be recouped into the combustor.

As shown in Table 1, operating with the auxiliary steam turbine produces a significant increase in thermal efficiency of 2.8 percentage point improvement when the auxiliary steam turbine is added. Also, there is provided a 14% horsepower improvement. It should be noted, that in the table, neither boiler pump horsepower nor power turbine rotor thrust bearing loss was accounted for in the performance. Also, the high pressure compressor operating line was not allowed to increase.

The size of an auxiliary steam turbine is quite small. A turbine approximately 7 inches long and 14 inches in diameter with one inch blading can put out approximately 6,600 horsepower with an efficiency of 0.875. For the example of Table 1, the steam flow of the above mentioned turbine would have to triple. The auxiliary steam turbine output can be geared right into the main shaft of the electrical generator as shown in Fig. 1. As shown in Fig. 1, a 6 to 1 gearbox reduction to 3,600 R.P.M. can be utilized. For a counter-rotating power turbine, a two-stage gear reduction to 1,800 R.P.M. would be utilized.

Fig. 3 shows a T-S (temperature-entropy) drawing for the Rankine cycle passing through the engine heretofore shown in Fig. 1. The steam injected into the main combustor would follow line 60 and reach point a. The steam would then pass through the various turbines with the reduction of temperature and pressure as shown along line 62 to reach point b. Should a supplementary burner be included after the power turbine, the steam would increase its temperature to point c with the output of the steam then being exhausted back through the exhaust stack at point f.

Without the use of the present invention, steam would initially enter along line 64 and proceed along line 66 until it is injected into the main combustor. With the presence of the high pressure boiler, the steam proceeds along the curved line 68 until it reaches point d at the entrance to the auxiliary steam turbine. The temperature and pressure is then reduced through the auxiliary steam turbine along line 69 until point e is reached. At this point, the temperature and pressure is still adequate for main combustor heating.

It should be appreciated, that the area betweeen the lines 66, 68 and 69 presents additional area under the curve. As is well known, any such additional area under the curve provides improved efficiency to the cycle as long as the exhaust stack temperature is at the same level.

Accordingly, using the present invention, the overall cycle thermal efficiency is improved. Additionally, direct recovery of horsepower can be made through the use of the high pressure boiler with the auxiliary steam turbine, whereby less uncondensed vapor leaves the exhaust at a given fuel flow rate.

Although the present invention has been described in connection with specific examples and embodiments, it will be recognized by those skilled in the various arts involved that other embodiments and modifications can be made without departing from scope of the invention as represented by the appended claims.

TABLE I

HIGH PRESSURE TURBINE ROTOR INLET PRESSURE AND TEMPERATURE HELD CONSTANT		
	Base case	Case with auxiliary Steam turbine
Total horsepower to generator	126983 (95 MW)	144451 (108 MW)
System thermal efficiency	0.427	0.455 (+2.8 points)
Main combustor fuel flow - lb/hr	26263	28942
Supplementary combustor fuel flow - lb/hr	13576	13591
Power Turbine shaft horsepower	126983	124766
Auxiliary Steam turbine shaft horsepower	0	19685
Steam flow to main combustor lb/sec	83.0	82.3
°F temperature of steam to main combustor	1292	916
Steam flow to LPT - lb/sec	83.4	9.3
°F temperature of steam to LPT	746	1016
°F gas temperature to LPT	1633	1606
°F gas temperature to PWT	1507	1478
°F gas exit temperature from PWT	847	831
°F supplentary combustor exit gas temperature	1347	1331
°F exhaust stack exit gas temperature	278	293
°F HP boiler temperature	1294	1278
HP boiler pump horsepower	310	1024
LP boiler pump horsepower	11	11
Notes: Boiler & Pumps increased horse power not accounted for in performance (approx. 1/2%)		

Claims

1. A steam injected gas turbine engine, comprising: in series combination, a compressor, a combustor, a high pressure turbine, and an output power turbine for producing the output from the engine, and further comprising a high pressure boiler means downstream of the power turbine providing superheated steam for injection into the engine, and an auxiliary steam turbine receiving the steam from the high pressure boiler prior to injection of that steam into the engine for extracting additional power output from the engine to increase engine output power and thermal efficiency.

2. A steam injected gas turbine engine as in Claim 1, and comprising means for injecting the superheated steam into the combustor.

3. A steam injected gas turbine engine as in Claim 2, and further comprising a superheater for reheating the steam prior to injection into the combustor.

4. A steam injected gas turbine engine as in Claim 3, wherein said superheater is downstream of said power turbine and upstream of said high pressure boiler means.

5. A steam injected gas turbine engine as in Claim 1, and comprising means for utilizing said steam for cooling hot parts of the engine.

6. A steam injected gas turbine engine as in Claim 5, wherein said hot parts include static vane parts.

7. A steam injected gas turbine engine as in Claim 1, and further comprising an auxiliary turbine gear box coupled to said auxiliary steam turbine to obtain an output at a desired speed.

8. A steam injected gas turbine engine as in Claim 1, and further comprising a variable speed constant frequency device coupled to said steam turbine to obtain an output at a desired speed.

9. A steam injected gas turbine engine as in Claim 1, wherein said engine includes a counter-rotating power turbine, and further comprising a two-stage gear reduction means coupled to said auxiliary steam turbine to obtain an output at a desired speed.

10. A steam injected gas turbine engine as in Claim 1, and further comprising additional boiler means downstream of said high pressure boiler means operating at lower pressure and producing steam for injection into parts of the engine.

11. A steam injected gas turbine engine as in Claim 10, wherein said engine further comprises a low pressure turbine and wherein said additional boiler means comprise an intermediate pressure boiler for producing steam for injection into at least one of said high pressure turbine and said low pressure turbines.

12. A steam injected gas turbine engine as in Claim 1, and further comprising a low pressure boiler means for producing steam for injection into the power turbine.

13. A steam injected gas turbine engine as in Claim 10, and further comprising auxiliary compressors driven by said auxiliary steam turbine, said auxiliary compressors pressurizing the steam from said additional low pressure boilers and means for injecting the steam from the auxiliary compressors into the combustor.

14. A steam injected gas turbine engine as in Claim 1, wherein said high pressure boiler means produces superheated steam having a pressure in the range of 1,500-3,500 psia.

15. A steam injected gas turbine engine as in Claim 1, wherein said high pressure boiler means produces superheated steam at a temperature of at least 50° above saturation.

16. A method of improving the power output and thermal efficiency of a steam injected gas turbine engine having a compressor, a combustor, a high pressure turbine, and a power turbine, in series combination, the method comprising: generating superheated steam in a high pressure boiler downstream of the power turbine, extracting horsepower from the generated steam in an auxiliary steam turbine, and injecting the steam exiting from the auxiliary steam turbine back into the engine.

17. The method as in Claim 16, wherein said steam is injected into the combustor.

18. The method as in Claim 16, and further comprising the step of reheating the steam prior to injecting it back into the engine to reduce the amount of uncondensed steam leaving the open cycle.

19. The method as in Claim 16, wherein said steam is used for cooling static vane parts of the engine.

20. The method as in Claim 16, wherein the output of the auxiliary steam turbine operates through an auxiliary turbine gear box directly into the main output of the power turbine.

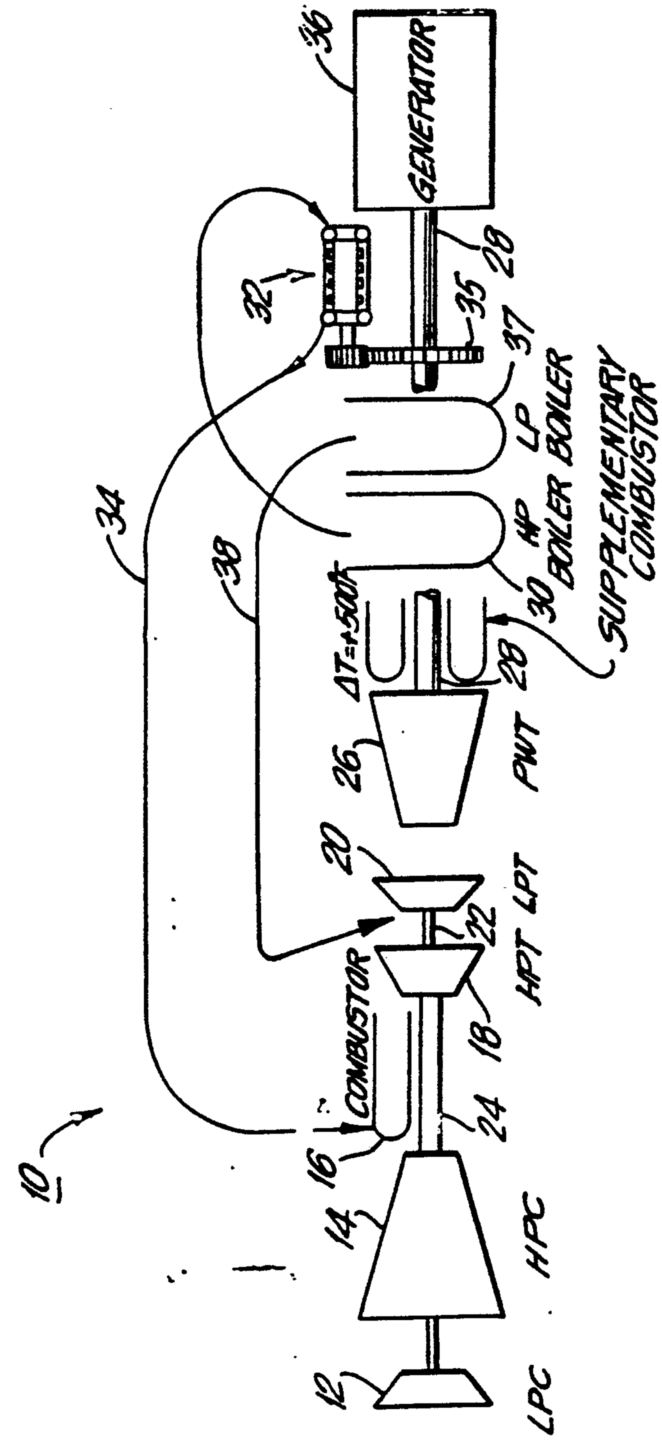
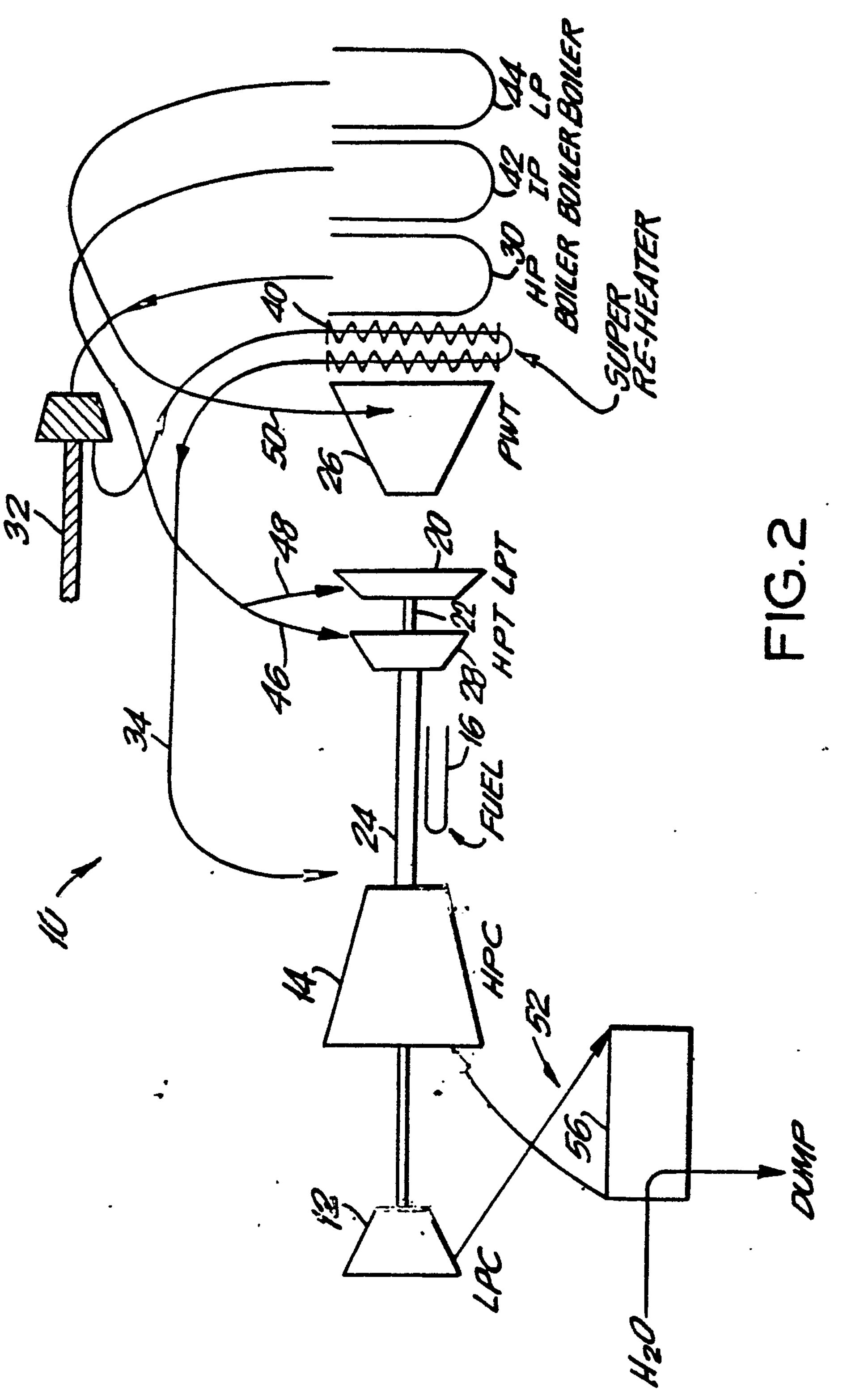

GENERATOR
36
32
35
28
37
LP BOILER
HP BOILER
30
SUPPLEMENTARY COMBUSTOR
34
38
ΔT=+500F
28
PWT
26
20
LPT
HPT
22
18
COMBUSTOR
24
16
14
HPC
12
LPC
10

FIG.1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HPC
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PWT
32
40
SUPER
RE-HEATER
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BOILER
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IP
BOILER
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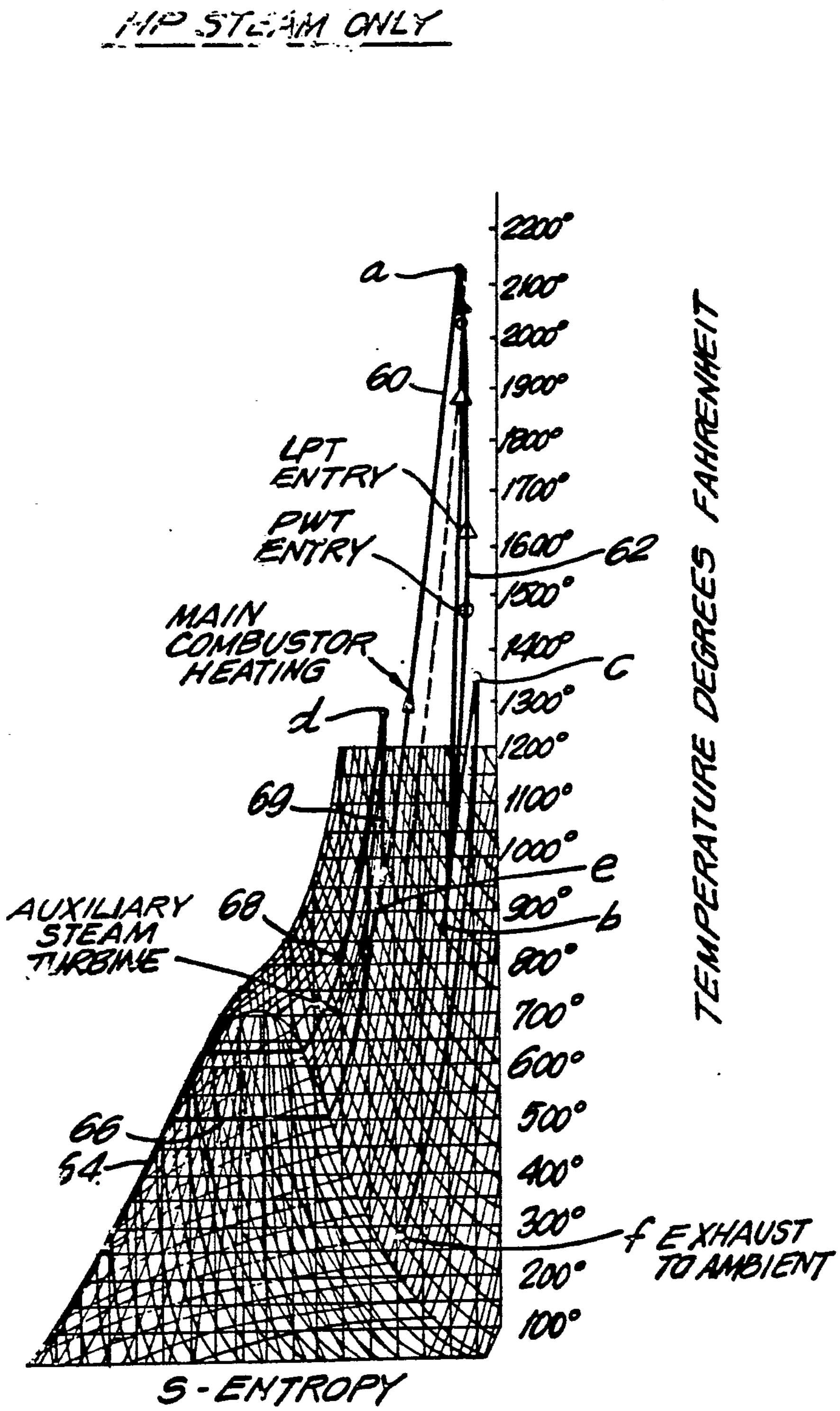
LP
BOILER
52
56
DUMP
H_2O

FIG.2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LPT ENTRY
PWT ENTRY
MAIN COMBUSTOR HEATING
d
69
AUXILIARY STEAM TURBINE
68
66
64
62
C
e
b
f EXHAUST TO AMBIENT
2200°
2100°
2000°
1900°
1800°
1700°
1600°
1500°
1400°
1300°
1200°
1100°
1000°
900°
800°
700°
600°
500°
400°
300°
200°
100°
TEMPERATURE DEGREES FAHRENHEIT
S-ENTROPY

FIG.3